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SUMMARY

The selection of spectrometric techniques for the measurement of stream temperatures in arc-heated facilities is discussed with respect to the properties of the gas stream. The stream properties were found to be important in the selection of methods for, and the interpretation of, such temperature measurements. Representative temperature measurements are presented which demonstrate the effects of optical thickness, stream composition, and temperature gradients on spectrometric measurements. In addition, the results of these spectrometric measurements are compared with nonspectrometrically determined temperatures.

INTRODUCTION

The technique of heating air by means of electric arcs has advanced sufficiently that many electric arc-powered facilities are in use for simulating high-temperature entry environments. Spectrometric techniques have been adapted to the measurement of stream temperature in these facilities. The problems of the selection of a method of temperature measurement and of interpretation of the results from the standpoints of local thermodynamic equilibrium and steady-state temperature gradients have been discussed in the literature (ref. 1). The spectral properties of the gas stream of any given arc facility should also be considered in selecting a technique and interpreting data, inasmuch as the radiating species in the gas, the spectral emissivity of the gas, and temperature gradients and fluctuations all affect the technique selection.

The fundamental problem in measuring arc-heated airstream temperatures is that no one temperature can be ascribed to the stream, even if local thermodynamic equilibrium exists, because temperature gradients and fluctuations are present within the stream. Care must be exercised, therefore, in interpreting measured temperatures to determine the type of averaging process inherent in the measurement technique. Furthermore, the stream characteristics must be considered when temperature measurements are used in the analysis of materials, structures, or aerodynamic test data obtained in such facilities. One assumption frequently made in spectrometric temperature measurements is that the stream is optically thin. The use of techniques, based on this assumption, in streams with appreciable optical thickness can lead to large errors in temperature measurements.

This paper describes the results of an experimental program, supplemented by theoretical considerations, in which four spectrometric and two nonspectrometric methods for temperature measurement were applied to three different arc-heated gas streams. Some of the effects of gas composition, temperature fluctuations and gradients, thermodynamic equilibrium, and optical thickness on the various methods are described. The specific measurement methods are briefly described, and representative sets of experimental data are used to compare the techniques and point out the limitations of each method.

SYMBOLS

a	amplification factor
I	spectral intensity
I_B	spectral intensity of black body
j	spectral emission coefficient
K	parameter defined as $\gamma \dfrac{I_{B,2}}{I_{B,1}}$
k	spectral absorption coefficient
N	particle number density
R	ratio-recorder deflection
S	photomultiplier sensitivity
x	linear dimension
γ	ratio of emission coefficients
$\Delta\lambda$	wavelength interval
ϵ	integrated spectral emissivity
θ	angle formed by oscilloscope trace and base line
τ	optical thickness

Subscripts:

1	first wavelength
2	second wavelength

g gas

l tungsten ribbon-filament lamp

SPECTROMETRIC MEASUREMENT TECHNIQUES

Of the many available methods for the spectrometric determination of gas temperature, four will be discussed in this paper. These are the intersection-wave-number (ref. 2), the reduced-top-height-ratio (ref. 3), a spectral-radiance (ref. 4), and the atomic-line-intensity-ratio (ref. 5) methods. These methods depend on the measurement of line or spectral intensities instead of line profiles and are most easily applied in the gas temperature range between 3,000° K and 5,000° K. The methods described in this paper also depend on the radiation of contaminating species ablated from the electrodes of the arc unit, inasmuch as the working gas used in atmospheric entry simulation (air) does not radiate strongly in the temperature range of most facilities. A discussion of the manner in which chemical composition, as well as thermodynamic equilibrium, optical thickness, and temperature gradients and fluctuations affect method selection will be presented in a subsequent section.

Intersection-Wave-Number Method

The intersection-wave-number method is useful primarily in carbon-arc-heated air facilities, inasmuch as it utilizes the radiation of the cyanogen molecule, which is present in the airstream due to the combination of nitrogen in the air and carbon from the electrodes. The rotational lines in the tail of the $0 \rightarrow 1$ vibrational transition band of the $^2\Sigma \rightarrow {}^2\Sigma$ electronic transition system are used as described in reference 2. In this method, intensities of the lines to be used are calculated according to the Boltzmann equation and plotted as a function of temperature. Advantage is taken of the two-branch form of the band in such a way that the parameter dependent on temperature is not an intensity or intensity ratio, but a wave number or wavelength. (See ref. 2.) This is the wavelength at which the two branches of the band are of equal intensity. This use of wavelength makes the measured temperature insensitive to the gas emissivity, and hence the method may be used in systems where the optical thickness of the gas stream has not been determined. As pointed out in reference 2, this method yields a temperature describing the rotational energy states of the cyanogen molecules and is essentially independent of all other energy distributions.

The sensitivity of the method is about 100° K for a change of 1 kayser $\left(\text{cm}^{-1}\right)$ in intersection wave number, and the sensibility (or temperature resolution) is about 200° K. The scatter band width in the measurements presented in this paper is 500° K, and the absolute error is estimated to be less than ±400° K.

Reduced-Top-Height-Ratio Method

The reduced-top-height-ratio method, discussed in reference 3, is based on the $0 \rightarrow 0$ and $1 \rightarrow 1$ vibrational bands of the $^2\Sigma \rightarrow {}^2\Sigma$ electronic transition of the cyanogen molecule and consists of deducing the temperature from the ratio of the head intensities of these two bands. The intensity of the $1 \rightarrow 1$ band head is corrected for the interference by the tail of the $0 \rightarrow 0$ band which appears at the same wavelength. Temperatures derived by this technique are necessarily vibrational mode temperatures.

The assumption of an optically thin layer of radiating fluid is made. Increasing optical thickness tends to equalize the band head intensities and to increase the relative intensity of that part of the $0 \rightarrow 0$ band to be subtracted from the $1 \rightarrow 1$ band head. The resulting temperatures will tend toward 8,000° K with increasing thickness since this is the temperature at which the band head intensities would be equal in the optically thin case.

The accuracy of this method is discussed quite fully in reference 3. Systematic errors are not easily estimated, but perhaps an error of less than 600° K can be assured by careful examination of the band profiles for the detection of interfering radiation. The sensitivity is given in the reference as 100° K for a 1-percent change in intensity ratio. Inaccuracies in experimental intensity measurements can lead to 5-percent uncertainty in the intensity ratio and, hence, a scatter band of ±500° K.

Spectral Radiance Method

The radiation from a black body or optically thick gas is completely described by the Planck equation. Although the radiation from a gas is seldom a truly black-body radiation, in some cases spectral regions may be found in which the radiation intensity closely approaches the Planck expression. (See discussion in ref. 4.) When this occurs, the spectral emissivity is said to be nearly 1, and a simple absolute intensity measurement at that wavelength can yield highly accurate temperature measurements. Temperatures measured by this technique have little meaning unless thermodynamic equilibrium exists in the gas stream, inasmuch as the Planck equation applies only to sources in the equilibrium state.

The sensitivity of this method of temperature measurement is generally high, particularly at shorter wavelengths, but is strongly dependent on the wavelength and temperature. In the measurements to be reported in this paper, a wavelength of 3,883 angstroms was used, and, at a temperature of 3,600° K, the sensitivity is 2° K for a 1-percent change in intensity. The primary sources of error in this measurement technique are in the intensity of the calibration source and in the uncertainty as to the true emmissivity of the gas. The high sensitivity of the measurements usually allows these errors to be kept to less than 100° K.

Atomic-Line-Intensity-Ratio Method

The atomic-line-intensity-ratio method, as applied to the measurement of temperatures in copper arcs, is outlined in reference 5. It consists simply of measuring the ratio of intensities occurring at 5,153 and 5,700 angstroms and obtaining a corresponding temperature for this ratio as calculated from the Boltzmann equation. (See fig. 1.) Temperatures measured by this technique correspond to the electronic excitation temperature of the copper atoms in the airstream.

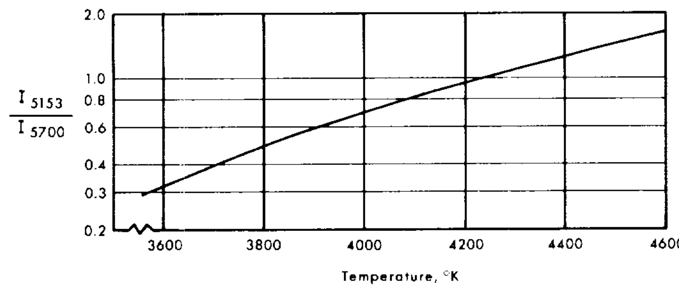

Figure 1.- Copper-line intensity ratio as a function of temperature (from ref. 5).

The correctness of the results will depend on the validity of the assumption of an optically thin stream unless the calculation of intensities is corrected for a known spectral emissivity. The sensitivity of this method is approximately 7.5° K for a 1-percent change in intensity ratio. The sensibility depends on the experimental technique, but can be as high as 2 percent, or 15° K. The calibration lamp intensity ratio is only slightly dependent on temperature at these wavelengths, and hence only about a 2-percent error in intensity ratio is introduced by the uncertainty of the calibration lamp temperature. Experimental errors in alinement of the instrument, and so forth, have been found to contribute an error of about ±70° K.

NONSPECTROMETRIC MEASUREMENT TECHNIQUES

Although this paper is concerned principally with spectrometric temperature measurements, some significant points should be made about their comparability with nonspectrometric measurements. Of all the various methods by which the gas temperature can be determined, perhaps the most easily understood is the heat-balance method, whereas the method most directly applicable to structures and materials tests is the heat-transfer-rate method. Both indicate the gas enthalpy, from which the temperature is deduced through a knowledge of the gas properties. The necessary gas properties have been calculated for most of the gases of interest (refs. 6 and 7). The enthalpy or temperature will be used where convenient, with the appropriate conversions as necessary.

Heat-Balance Method

The heat-balance method consists simply of subtracting all energy losses from the total energy input; this difference is assumed to yield the average energy in the gas stream. The accuracy of the gas enthalpy determination is dependent upon how well all the losses can be accounted for and measured. Errors are possible when the losses are a large portion of the total power input. The method yields the average enthalpy and hence does not define the enthalpy at a given point or during a short time interval.

Heat-Transfer-Rate Method

A stagnation temperature can be calculated from the experimentally determined stagnation heat transfer rate on a body of a given shape and size if the stagnation pressure and the free-stream Mach number are known. A relationship presented in reference 8 gives the stagnation-point heat transfer rate as a function of the stagnation properties and the velocity gradient. Reference 9 describes the application of this theory to the measurement of gas enthalpy for the particular jet in which the measurements reported in this paper were made. The theory predicts heat transfer rates to within ±10 percent.

The local gas stagnation temperatures determined by the heat-transfer-rate method are average temperatures because of thermal lag in the sensing device and are therefore insensitive to stream temperature fluctuations. It should be noted that, for this reason, the temperatures determined by this technique can be applied to the reduction of data obtained from materials tests in a fluctuating stream since the test samples average fluctuations in a similar manner. Temperatures determined from measurements of the heat transfer rate relate most directly to the translational temperature of the gas. However, if the heat transfer rate is measured to a catalytic surface, the gas ionization temperature will affect the measurement.

FACTORS AFFECTING MEASUREMENT TECHNIQUE SELECTION

Gas Composition

The selection of a spectrometric method or methods for the measurement of temperatures in a particular arc facility must be made on the basis of arc unit design, inasmuch as the radiating species in the stream consist primarily of contaminants from the electrode material. Most arc units can be classified in two groups: those using carbon electrodes, and those using metallic electrodes. When carbon electrodes are used, it has been found that the entire visible spectrum is dominated by carbon and cyanogen band spectra, with various atomic lines superimposed on the molecular bands. For this case, methods utilizing band intensities are more easily used for temperature measurements. When metallic electrodes are used, the spectrum of the gas is usually dominated by the atomic spectrum of the electrode material, with various weak metallic oxide or working gas bands. For this case, it is frequently possible to find useful atomic lines free from interfering radiation, whereas the band spectrum is too weak to be easily used.

Local Thermodynamic Equilibrium

The question of thermodynamic equilibrium has been discussed at length in several references (for example, refs. 1, 3, 4, and 10), and therefore a detailed treatment of this complex subject will be avoided. Inasmuch as spectrometric methods do not depend on the general state of the gas, but only on a small number of energy states in one atomic or molecular specie present, any one of the methods discussed provides very little information about the state of the gas unless the gas is in thermodynamic equilibrium. It is necessary, therefore, to have some confidence that thermodynamic equilibrium does exist in the gas if only one spectrometric technique is to be used. Various authors have shown (for example, refs. 1 and 10) that local equilibrium can be expected in most arcs at atmospheric pressure. In arc units of reasonable size at atmospheric pressure the heat transfer processes in the gas are collision controlled since the collision frequency is high (on the order of 10^8 collisions per second) and the radiation field intensity is low. Again, because of the high collision frequency, the gas remains in thermodynamic equilibrium despite changes in pressure and velocity in the arc chamber and heat losses to the chamber walls. If, then, a subsonic nozzle is used, it appears reasonable to assume that the gas is in local thermodynamic equilibrium in the test portion of the stream. Supersonic nozzles exhausting to atmospheric pressure do not induce sufficiently rapid changes in pressure and density to induce a nonequilibrium state at Mach numbers below about 3. If there is reason to suspect nonequilibrium conditions in the gas, agreements between different spectrometric measurement techniques or between a spectrometric and nonspectrometric technique may be taken as evidence that equilibrium exists.

The heat-balance method previously discussed yields the gas enthalpy even in a nonequilibrium condition, although the usefulness of such a measurement can be severely questioned. On the other hand, the heat-transfer-rate method depends only on the translational and ionization stagnation temperatures of the gas.

Temperature Gradients and Fluctuations

As previously pointed out, the temperatures across an arc-heated gas stream may not be uniform and may also vary with time. These conditions should therefore be taken into account in the selection of a measurement method and in the interpretation of the results. For instance, the heat-balance method yields an average enthalpy over the stream cross section. The heat-transfer-rate method gives the stagnation enthalpy in the neighborhood of the stagnation point of the sensing device.

When temperature gradients occur along the line of sight through a gas stream, spectrometric measurements give average temperatures weighted toward the highest temperatures along this line of sight. If these gradients exhibit cylindrical symmetry, the analytical method given in reference 1 can be used to determine local temperatures within the stream. This analysis requires a knowledge of the intensity variations across the stream. Photographic or scanning photoelectric techniques may be employed to obtain these variations.

Timewise fluctuations in temperature also frequently exist, and, of course, the response characteristics of the measuring system will be a factor in the indication of temperature. Of the methods discussed, the heat-balance method has the slowest response, whereas the spectrographic intensity methods using electronic computing and readout circuits may be designed for almost any desired frequency response. Most arc-heated airstreams exhibit both temperature gradients and fluctuations. If both gradients and fluctuations are significant, the interpretation of spectrometric data in terms of local instantaneous or average temperature is not possible. Heat-balance measurements cannot be interpreted if either gradients or fluctuations exist. The heat-transfer-rate method is the only method discussed in this paper which yields local time-average temperature measurements when both gradients and fluctuations are present.

Optical Thickness

Inasmuch as the case of gradients symmetrical with respect to optical thickness have been discussed in the literature (ref. 1), this paper treats only the case of a homogeneous layer of gas. Figure 2 shows the dependence of the integrated spectral emissivity of a homogeneous gas layer as a function of the optical thickness of the layer, as calculated from equation (A5) in appendix A.

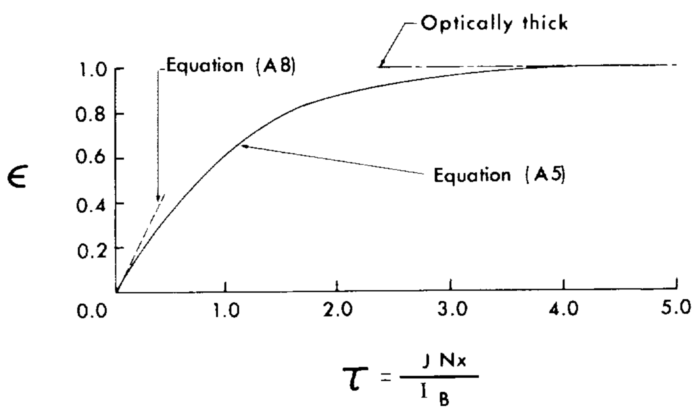

Figure 2.- Integrated spectral emissivity of a homogeneous gas layer as a function of optical thickness.

The reason for the effect of optical thickness on spectrometric measurements is that the absorption of the gas depends on the emitted spectral intensity. Thus, when the integrated spectral emissivity of the gas is small, it is valid to neglect the absorption; whereas, at high emissivities, absorption plays a very important role. This effect is shown graphically in figure 2. Figure 3 shows the effect of gas emissivity on the ratio of spectral emissivities which correspond, according to equation (A5), to the spectral intensities. This figure shows that the ratio is appreciably affected only if the stream is very thick optically. It can be shown from figure 3 that temperature measurements obtained from the line-intensity-ratio method based on the assumption of an optically thin gas are limited to streams with an integrated spectral emissivity of less than 0.10. In the region of appreciable change, very accurate emissivity measurements are necessary to obtain a satisfactory interpretation of the temperature measurements. It will be noted that the effect of optical thickness can be detected by changing the geometrical thickness of the gas layer an order of magnitude if absorption is affecting the intensity ratio.

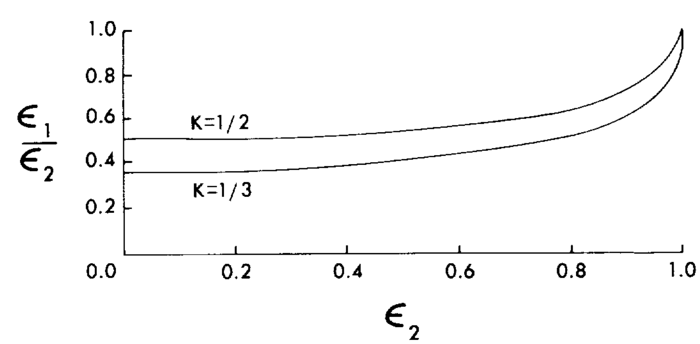

Figure 3.- Normalized intensity ratio as a function of integrated spectral emissivity (from eq. (A13)).

If the integrated emissivity is above about 0.85, it is much more convenient to use the absolute spectral intensity as a temperature-measuring parameter. Only one intensity (at some given wavelength) must be measured to determine the temperature, and the sensitivity of the method is much higher than that of the various intensity-ratio methods. The error in temperature due to uncertain emissivity is usually less than the uncertainty imparted by the same unknown in the intensity-ratio methods.

It has been previously pointed out that the intersection-wave-number method is unusual in that the temperature indication is unaffected by absorption. The sensitivity is reduced in that the difference in the line intensities becomes less certain as emissivities over about 0.85 are encountered. When usable, this method forms a convenient bridge in the emissivity range where correction for absorption is difficult with the usual methods, but where the spectral radiance method is not applicable.

The heat-transfer-rate method depends on a theory which does not take into account any radiant heating and, therefore, can give erroneous temperatures if the gas-stream emissivity is high. The heat-balance method of temperature determination is completely insensitive to the radiation of the gas and, therefore, is unaffected by the gas-stream optical thickness.

EXPERIMENTAL TEMPERATURE MEASUREMENTS

Temperatures were measured in three arc-powered facilities by using the methods described in this paper. The results of two of these sets of temperature measurements serve to illustrate some of the effects of temperature gradients and optical thickness on temperature measurements, whereas one set illustrates the apparent absence of such effects.

Apparatus and Techniques

Table I lists the important characteristics of the arc-heated facilities. The 700-kilowatt arc-powered jet at the Langley Research Center is a supersonic (Mach 2) facility. (See refs. 2 and 11.) Temperature measurements made in this facility are classified as to whether temperatures relate to the free-stream or stagnation condition. The other facilities in which temperature measurements

TABLE I.- CHARACTERISTICS OF ARC FACILITIES

Facility characteristics	700-kilowatt arc jet	1,500-kilowatt arc tunnel	2,500-kilowatt arc jet
Power, kw	500 to 700	1,000 to 1,500	600 to 2,500
Mass flow, lb/sec	0.06 to 0.10	0.10 to 0.20	0.06 to 0.35
Stream diameter, in.	0.52	6.00	4.00
Arc-chamber pressure, psia	150	15	15
Discharge pressure, psia	15	0.15	15
Mach number	2	0.10	0.05
Stagnation temperature, °K	4,000 to 6,000	3,000 to 4,000	3,500 to 4,300
Electrode material	Carbon	Carbon	Copper
Contamination, percent by weight	7	20 to 40	0.1

were made operate at low subsonic velocities, and the difference between stagnation and free-stream temperatures is indistinguishable.

The characteristics of the spectrometric equipment used for these measurements are given in the following list. The prism spectrograph was significantly modified for these measurements; the details of these modifications are described in appendix B.

Ebert mount 2.25-meter spectrograph:
- Characteristics -
  - Grating: $1\frac{1}{2}$ by 3 inches; 15,000 lines per inch
  - Photographic f-number: 54
  - Dispersion: 5 angstroms per millimeter
- Data-collecting systems -
  - Photographic: two 4- by 10-inch plates
  - Photoelectric: two exit slits, one scanning and one fixed, used with ratio strip-chart recorder

Medium glass-prism spectrograph:
- Characteristics -
  - Photographic f-number: 12
  - Shutter: light-integration controlled
  - Plate racking: shutter operated
  - Dispersion: 22 angstroms per millimeter at 4,200 angstroms
- Data-collecting systems -
  - Photographic: one 4- by 10-inch plate
  - Photoelectric: two adjustable fixed slits, used with ratio strip-chart recorder, oscilloscope, or null-balance indicator

In performing measurements in a 1,500-kilowatt tunnel, the 6-inch subsonic arc tunnel at the Langley Research Center, provision was made for varying the physical and, hence, optical thickness of the gas stream. This was accomplished by the use of optical probes mounted on the walls of the tunnel test section, as shown in figure 4. The distance between the circular discs was varied to change the thickness of the stream observed. The discs were designed with sharp edges so as to minimize disturbance of the subsonic gas stream. Erosion of the discs was found to be very small even for long periods of operation.

The combinations of measurement techniques and spectrometric apparatus used to measure temperatures in each facility are shown in table II. The combinations given in the table were chosen to illustrate the limitations imposed by stream conditions as well as to provide a comparison of methods and an accurate temperature measurement in each facility.

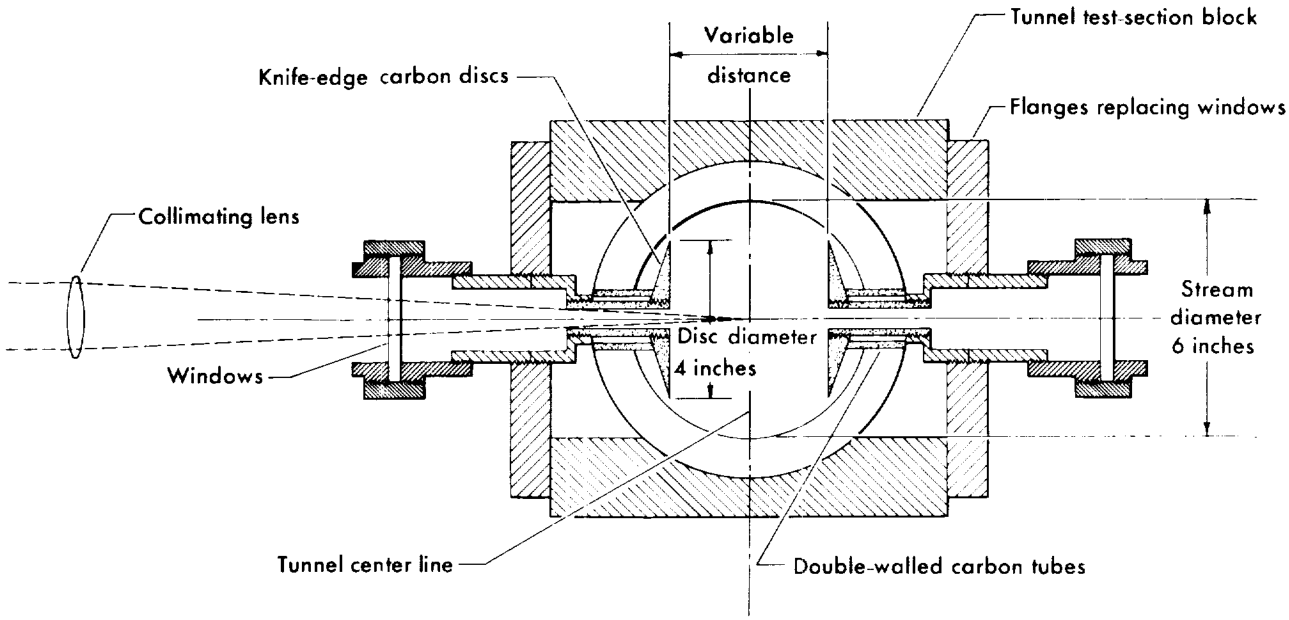

Figure 4.- Cross section of 1,500-kilowatt arc tunnel showing placement of optical probes.

TABLE II.- TEMPERATURE-MEASUREMENT COMBINATIONS

Facility	Measurement technique	Measurement system	
		Measurement instrument	Readout system
700 kilowatt	Heat transfer rate Reduced top-height ratio Intersection wave number	Probe Prism spectrograph Grating spectrograph	Oscillograph Photographic Photographic
1,500 kilowatt	Reduced top-height ratio Spectral radiance Intersection wave number	Prism spectrograph Grating spectrograph Grating spectrograph	Photographic Photoelectric Photographic
2,500 kilowatt	Atomic-line-intensity ratio Heat balance	Prism spectrograph See section entitled "Heat-Balance Method"	Photoelectric See section entitled "Heat-Balance Method"

Discussion of Results

Table III presents temperatures measured in the 700-kilowatt arc-powered jet by three different methods. The agreement between temperatures measured by the different techniques indicates that the stream is in thermodynamic equilibrium, that the radiation used in the reduced-top-height-ratio measurements is optically thin, and that no extreme temperature fluctuations occurred in the stream at the point of measurement. Since the intensity of radiation from the jet stream was found to be highly variable, this last conclusion indicates that such variations

TABLE III.- MEASURED TEMPERATURES IN 700-KILOWATT ARC-POWERED JET

Test points	Free-stream temperature, °K		Recovery temperature, °K	
	By the intersection-wave-number method (a)	By the reduced-top-height-ratio method	By the reduced-top-height-ratio method	By the heat-transfer-rate method
1	4,500		$5,025 \begin{smallmatrix} +275 \\ -275 \end{smallmatrix}$	4,800
2	5,000		$5,150 \begin{smallmatrix} +150 \\ -150 \end{smallmatrix}$	5,250
3	4,800	$4,300 \begin{smallmatrix} +300 \\ -400 \end{smallmatrix}$		4,800
4	4,400	$4,560 \begin{smallmatrix} +140 \\ -60 \end{smallmatrix}$		4,000
5	4,800	$5,040 \begin{smallmatrix} +360 \\ -440 \end{smallmatrix}$		5,700

[a]Temperatures given in this column were obtained from reference 2 where arc power was used to correlate test points. The other temperatures given for each test point were measured simultaneously by synchronizing the spectrograph shutter with the insertion of the heat-transfer-rate probe.

may be due primarily to changes in contamination level, rather than to temperature changes.

The results of temperature measurements in the 1,500-kilowatt arc tunnel are presented in figure 5. This figure shows the temperatures measured by the various methods as a function of the distance between the ends of the optical probes placed in the tunnel test section. The tunnel operating conditions were kept as constant as possible during all these measurements. The intersection-wave-number method, which is independent of optical thickness, agrees well with the spectral-radiance method as applied at 3,883 angstroms (the head of the 0→0 cyanogen band) and indicates the high emissivity of the stream at that wavelength. It should be noted that the temperature indicated by the reduced-top-height-ratio method decreases from 8,000° K toward the true gas temperature as the geometric depth of the gas layer is decreased. This indication is exactly as would be predicted, since 8,000° K is the temperature indicated by the reduced-top-height-ratio method at a spectral emissivity of 1. Such evidence leads directly to the conclusion that the spectral-radiance method is applicable to temperature measurements in this stream. This method was used because of its convenience and sensitivity for further temperature measurements in this facility.

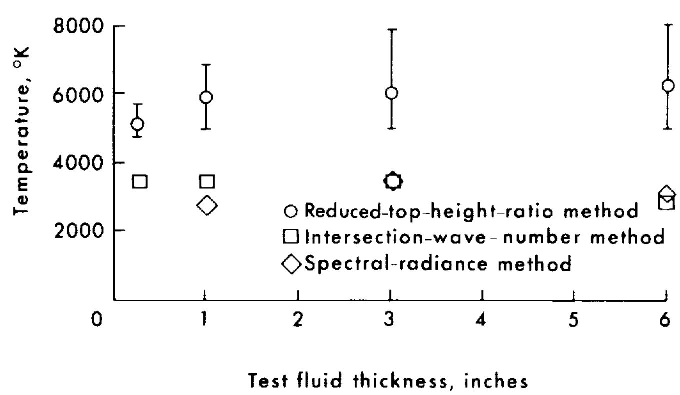

Figure 5.- Dependence of temperature measured by three methods as a function of test fluid thickness in 1,500-kilowatt arc tunnel.

Temperatures were measured in the 2,500-kilowatt arc jet at the Langley Research Center (ref. 12) by using the atomic-line-intensity-ratio method as applied to copper lines at 5,153 and 5,700 angstroms and by means of a simple heat balance performed on the arc apparatus. Approximate measurements were made of the absolute intensities of the two copper lines to insure that the assumption made in this technique of an optically thin gas stream was valid. The enthalpy, as measured by the heat balance, was found to be 2,250 Btu/lb, whereas a spectrometric measurement through the center of the jet yielded an enthalpy of 3,000 Btu/lb. The apparent disagreement between the two methods appears to be due to temperature gradients in the heated gas stream. Measurements close to the periphery of the jet indicated that a temperature-gradient region is found at radial distances from the nozzle axis between 1.5 and 2.0 inches, as shown in figure 6. These data were used to calculate the average enthalpy of the flow by assuming a constant dynamic pressure across the nozzle exit and by using the gas properties from reference 6. Figure 6 shows the enthalpy profile and the calculated gas-weight-flow profile of the jet used in these calculations. The result of the calculations was an average enthalpy of 2,240 Btu/lb, which is in good agreement with the heat-balance measurements. This comparison indicates that, although the heat-balance and spectrometric measurements can be made to agree through correct interpretation of both measurements, the heat-balance technique is not useful when local stream temperatures are required. The spectrometric measurements, on the other hand, appear to yield good local temperatures in this facility.

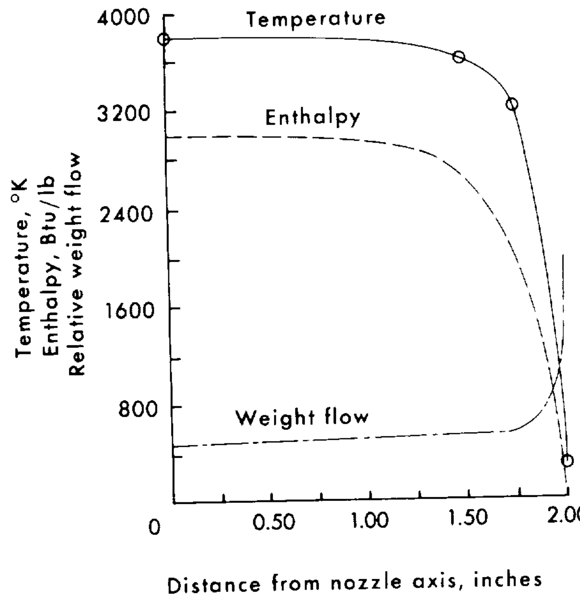

Figure 6.- Radial temperature, enthalpy, and mass-flow distributions at the nozzle exit of the 2,500-kilowatt arc jet.

CONCLUDING REMARKS

An experimental study of four spectrometric and two nonspectrometric methods of measuring the temperature or enthalpy of arc-heated air streams has been carried out and supplemented by theoretical considerations. In the experimental program, at least two of these methods were applied to temperature measurements in each of three different arc-heated air streams. In the 700-kilowatt arc-powered jet, the intersection-wave-number and reduced-top-height-ratio spectrographic methods and the heat-transfer-rate nonspectrometric method were all found to be applicable. The heat-transfer-rate method is probably the best method for use in this jet because time and position correlation can be obtained, whereas the two spectrometric methods yield only highest temperatures in time and position.

In the 1,500-kilowatt arc tunnel having an optically thick gas stream, the reduced-top-height-ratio method yielded erroneous temperatures, whereas the intersection-wave-number method and the spectral-radiance method agreed on the stream temperature. The spectral-radiance method was found to be the best method for temperature measurements in this stream because of its high sensitivity and applicability to time-resolved measurements.

The third facility studied, the 2,500-kilowatt arc jet, was amenable to heat-balance temperature determinations and to temperature measurements by the atomic-line-intensity-ratio method. Although both methods yielded interpretable measurements, the presence of the cool jet periphery reduced the usefulness of the heat-balance method. The atomic-line-intensity-ratio method was found convenient and extremely useful because of its ability to distinguish between the hot central portion of the jet and the cool boundary and to perform time-resolved measurements.

This experimental program pointed out the importance of (1) gas composition, (2) optical thickness, and (3) temperature gradients on the selection and interpretation of temperature-measurement methods, and demonstrated the fact that different temperature-measurement methods should be used in arc-heated gas streams of different characteristics.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 19, 1963.

APPENDIX A

OPTICAL-THICKNESS CONSIDERATIONS

Assume that radiation at any given wavelength emanating from a homogeneous gas layer of varying thickness is observed. The equation governing such radiation is (ref. 13):

$$\frac{dI}{dx} = -kNI + jN \tag{A1}$$

where the first term on the right side represents the absorption of radiation and the second term represents the spontaneous radiation of the gas. A solution of this equation for $I(0) = 0$ may be written as follows:

$$I = \frac{j}{k}\left[1 - \exp(-kNx)\right] \tag{A2}$$

The ratio j/k can be evaluated for convenience by considering I for large values of Nx, where the exponential term is small, and hence

$$\lim_{x\rightarrow\infty} I = \frac{j}{k} \tag{A3}$$

But it is well known that $\lim_{x\rightarrow\infty} I = I_B$ and hence $\frac{j}{k} = I_B$, which is an identity inasmuch as j, k, and I_B are all independent of x, so equation (A2) can be written as follows:

$$I = I_B\left[1 - \exp\left(- \frac{jNx}{I_B}\right)\right] \tag{A4}$$

The integrated spectral emissivity is defined as

$$\epsilon = \frac{I}{I_B} = 1 - \exp\left(- \frac{jNx}{I_B}\right) \tag{A5}$$

and the gas optical thickness is defined as

$$\tau = \frac{jNx}{I_B} = -\log(1 - \epsilon) \tag{A6}$$

Consider now the limit of equation (A2) at small values of x. Expanding the exponential term and dropping higher powers of x gives

$$I = jNx \tag{A7}$$

or

$$\epsilon = \frac{jNx}{I_B} \tag{A8}$$

Then, the ratio of two intensities can be written as

$$\frac{I_1}{I_2} = \frac{j_1}{j_2} \tag{A9}$$

for small values of x.

Consider, however, the ratio of two line intensities based on equations (A4) and (A6). From equation (A6),

$$-j = \frac{I_B}{Nx} \log(1 - \epsilon) \tag{A10}$$

and if, at a particular temperature,

$$j_1 = \gamma j_2 = -\frac{\gamma I_{B,2}}{Nx} \log\left(1 - \epsilon_2\right) \tag{A11}$$

then,

$$\frac{I_1}{I_2} = \frac{I_{B,1}}{I_{B,2}} \left\{ \frac{1 - \exp\left[\gamma \frac{I_{B,2}}{I_{B,1}} \log\left(1 - \epsilon_2\right)\right]}{1 - \exp\left[\log\left(1 - \epsilon_2\right)\right]} \right\} \tag{A12}$$

If $K = \gamma \frac{I_{B,2}}{I_{B,1}}$, equation (A12) simplifies to

$$\frac{\epsilon_1}{\epsilon_2} = \frac{1 - \left(1 - \epsilon_2\right)^K}{\epsilon_2} \tag{A13}$$

where ϵ is as defined in equation (A5). This function is plotted in figure 3 for $K = \frac{1}{2}$ and $K = \frac{1}{3}$.

APPENDIX B

MODIFICATION OF PRISM SPECTROGRAPH

The prism spectrograph used in this investigation was modified substantially to make possible the photographic and photoelectric investigations discussed. This appendix describes the modifications and presents the analyses used in the interpretation of the photoelectric data.

The primary advantage of using the prism spectrograph to perform measurements in arc-heated air facilities is that, because of its relatively low f-number, spectrograms can be obtained in exposure times as short as 0.05 second. Therefore, this type of instrument can be used to determine the variation of the spectral characteristics of the gas with time, or to obtain spectra at discrete times of particular interest. The gas streams investigated with this instrument do not emit radiation at a constant rate, so that short equal-time exposures do not provide consistent photographic response. It became necessary to make the length of each exposure dependent on the radiation intensity during the exposure time. Consistent photographic response was accomplished by using photoelectric intensity integration. A very small portion of the light entering the spectrograph is intercepted near the collimating lens, detected by a photomultiplier tube, and integrated electrically. Appropriate relays are actuated when the total radiant energy reaches a predetermined level, and constant photographic response is obtained regardless of the absolute intensity of the radiation from the arc jet. It has been found convenient to interpose a filter passing only those wavelengths of interest into the light beam striking the photomultiplier tube to make the system somewhat selective in its response to various wavelengths.

Because it was desired to take advantage of the short exposure times possible with this instrument in obtaining temperature history studies of the heated gas, a mechanism for rapid shifting of photographic plates was added to the spectrograph. This mechanism allows the plate to drop a specified distance at the end of each exposure. With this system, a series of 6 or 12 exposures each as short as 0.05 second and as close together as 0.2 second may be made.

An attachment was built to provide continuous recording of the intensity ratio of the copper lines at 5,153 and 5,700 angstroms for the atomic-line-intensity-ratio method of temperature measurement. Energy from the two copper lines passes through two fixed exit slits and falls on two photomultiplier tubes after reflection from two plane mirrors. The two slits are of the same width, and, since they are parallel to the focal plane of the instrument and hence not perpendicular to the light path, they are cut at an angle of 20° on one side to prevent blocking the light passage.

The signals from the two photomultipliers are amplified and recorded or displayed in any of a variety of ways, depending on the type of data desired. Four such systems are shown schematically in figure 7. Continuous intensity-ratio histories can be obtained by applying the two signals to a current-ratio strip-chart recorder. The recorder deflection is then a measure of the

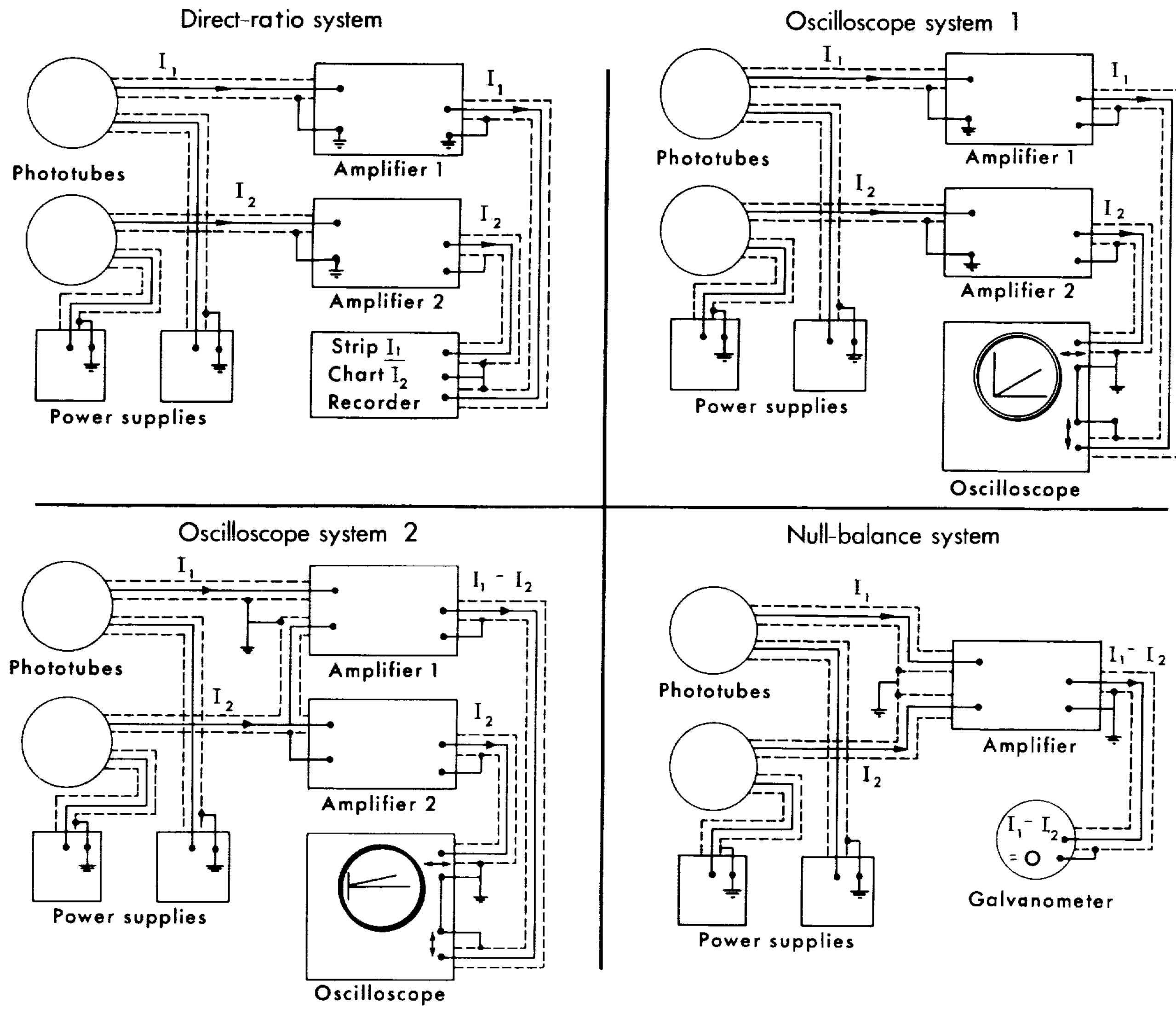

Figure 7.- Display systems for atomic-line-intensity-ratio measurement.

line-intensity ratio times a constant. The response time of such a system is limited to at least 0.25 second by the recorder. The response of the strip-chart recorder depends on the intensity ratio; thus, $R = \frac{I_1 S_1 a_1}{I_2 S_2 a_2}$ or, in terms of a calibration from a tungsten lamp with a ribbon filament $R_g = \left(\frac{I_1}{I_2}\right)_g \left(\frac{I_2 \Delta\lambda_2}{I_1 \Delta\lambda_1}\right)_l R_l$. This expression yields the gas intensity ratio in terms of the calibration deflection of the recorder, the recorder deflection due to the gas radiation, and the properties of the lamp and the spectrograph. It should be noted that the ratio of the wavelength intervals intercepted by the two exit slits, expressed as

$\frac{\Delta\lambda_2}{\Delta\lambda_1}$, is a factor in this expression. This factor appears in all atomic-line-intensity-ratio computations when a prism spectrograph, with a reciprocal dispersion which is dependent on wavelength, is calibrated with a continuum radiation, such as that from a tungsten filament. The presence of such a factor is due to the fact that both slits, if they are of appropriate width, intercept the entire line width, but intercept different wavelength intervals of the continuum radiation from the calibration source.

Two of the remaining systems, suggested in reference 1, utilize a cathode-ray oscilloscope to display the phototube signals. In the simpler system, the two signals are voltage amplified and applied to the horizontal and vertical deflection plates of the oscilloscope tube. The tangent of the angle the beam makes with zero-signal base line is then given by $\tan \theta = \frac{I_1 S_1 a_1}{I_2 S_2 a_2}$. An important feature of either this simpler oscilloscope system or the strip-chart recorder system is that a single proportionality constant can be adjusted so that the particular temperature range of interest is in the most sensitive range of the data readout system. It will be noted that the strip-chart system covers a range of only $R \leqq 1.00$ and, hence, a range of intensity ratio with some upper limit; whereas, the oscilloscope systems cover the entire range of intensity ratio independent of the proportionality constant.

The alternate oscilloscope method of presenting the data is much more versatile and sensitive but involves two calibration constants. In this system, the difference in the intensity signals is displayed as the ordinate, and one of the signals is displayed directly as the abscissa on the oscilloscope tube. The angle the oscilloscope trace makes with the horizontal is then given by:

$$\tan \theta = \frac{a_1}{a_2}\left(\frac{S_1 I_1}{S_2 I_2} - 1\right)$$

In this case, S_1/S_2 and a_1/a_2 must be determined separately. By adjusting these two constants appropriately, the sensitivity can be set to any desired value by adjusting a_1, and the temperature-range midpoint can be determined independently by adjusting S_1/S_2. Either of the oscilloscope systems is capable of following temperature changes at frequencies up to 10 kilocycles or greater, provided a high-speed recording can be obtained from the oscilloscope display. Maximum and minimum temperatures attained can be determined from visual or photographic observation of the oscilloscope face.

The highest accuracy in temperatures determined by the line-intensity-ratio technique can be obtained by using a simple null-balance system. The system is limited to steady-state measurements, as are all manual null systems. In this system, the difference of the two photomultiplier signals is indicated on a meter, and the sensitivity S_1 is adjusted so that no difference is indicated. This corresponds to the condition where $\theta = 0$ in the equation given in the preceding paragraph, and hence $\frac{I_1}{S_2} = \frac{I_2}{S_1}$. If the experimental measurements are performed such that $S_{2,g} = S_{2,l}$, the ratio of the equation for the measurement in gas to the equation for the calibration measurement gives, on simplification, the following equation for the intensity ratio in the gas:

$$\left(\frac{I_1}{I_2}\right)_g = \left(\frac{I_1 \Delta\lambda_1}{I_2 \Delta\lambda_2}\right)_l \frac{S_{1,l}}{S_{1,g}}$$

Calibration of these systems for both intensity-ratio and absolute-intensity measurement is carried out by using a tungsten ribbon-filament lamp, and, in the case of absolute-intensity measurement, the calibration is carried out while the lamp is in the position of the gas flow. Because dispersion in prism spectrographs is dependent on wavelength and because the focal plane of the instrument is inclined steeply with respect to the direction of the incident light, a correction was applied to the absolute-intensity measurements for this effect.

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